Mechanical Engineering Design

JOSEPH E. SHIGLEY

CHARLES R. MISCHKE

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Mechanical Engineering Design

Sixth Edition

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Table 7–13

Summary of Fatigue Equation $\mathbf{S}_e = \mathbf{k}_a k_b \mathbf{k}_c \mathbf{k}_d \mathbf{k}_e \boldsymbol{\phi}_{0.30} \bar{S}_{ut}$ in Customary Engineering Units for Steels*

Quantity	Relation	Table or Equation
Ultimate strength	$S_{ut} = 0.495\mathbf{LN}(1, 0.041)\mathbf{H}_B$	Eq. (5–23)
Fatigue ratio	$\boldsymbol{\phi}_{0.30} = 0.506\mathbf{LN}(1, 0.138)$, $\bar{S}_{ut} \le 212$ kpsi	Above Eq. (7–20)
Endurance limit		
Bending	$\mathbf{S}'_e = \boldsymbol{\phi}_{0.30}\bar{S}_{ut} = 0.506\bar{S}_{ut}\mathbf{LN}(1.\ 0.138)$, $\bar{S}_{ut} \le 212$ kpsi	Above Eq. (7–20)
Axial	$(\mathbf{S}'_e)_{ax} = 0.623\bar{S}_{ut}^{-0.0778}\bar{S}_{ut}\mathbf{LN}(1, 0.264)$	Above Eq. (7–20)
Torsion	$\mathbf{S}'_{se} = 0.166\bar{S}_{ut}^{0.125}\bar{S}_{ut}\mathbf{LN}(1, 0.263)$	Above Eq. (7–20)
Surface factor		
Ground	$\mathbf{k}_a = 1.34\bar{S}_{ut}^{-0.086}\mathbf{LN}(1, 0.120)$	Table 7–5
Machined, CR	$\mathbf{k}_a = 2.67\bar{S}_{ut}^{-0.265}\mathbf{LN}(1, 0.058)$	Table 7–5
Hot-rolled	$\mathbf{k}_a = 14.5\bar{S}_{ut}^{-0.719}\mathbf{LN}(1, 0.110)$	Table 7–5
As-forged	$\mathbf{k}_a = 39.8\bar{S}_{ut}^{-0.995}\mathbf{LN}(1, 0.146)$	Table 7-5
Size	$k_b = (d_e/0.30)^{-0.107} = 0.879 d_e^{-0.107}$	Eq. (7–10)
Loading factor		
Bending	$\mathbf{k}_c = \mathbf{LN}(1, 0)$	Eq. (7–20)
Axial	$\mathbf{k}_c = 1.23\bar{S}_{ut}^{-0.0778}\mathbf{LN}(1, 0.125)$	Eq. (7–21)
Torsion	$\mathbf{k}_c = 0.328\bar{S}_{ut}^{0.125}\mathbf{LN}(1, 0.125)$	Eq. (7–22)
Temperature factor	$\mathbf{k}_d$ (as applicable)	Eqs. (7–23), (7–24)
Miscellaneous factor	$\mathbf{k}_e$ (as applicable)	
Stress-concentration		
Infinite life	$K_6 = (\mathbf{K}_f)_{10^6} = \dfrac{K_t\mathbf{LN}(1, C_{Kf})}{1 + \dfrac{2}{\sqrt{r}}\dfrac{K_t - 1}{K_t}\sqrt{a}}$	Table 7–12
Finite Life	$\bar{K}_3 = (\bar{K}'_f)_{10^3} = 1 + \left[(\bar{K}_f)_{10^6} - 1\right]\left[-0.18 + 0.43(10^{-2})\bar{S}_{ut} - 0.45\left(10^{-5}\right)\bar{S}_{ut}^2\right]$	Eq. (7–27)
	$\bar{K}_N = \dfrac{\bar{K}_3^2}{\bar{K}_6} N^{(-1/3)\log(\bar{K}_3/\bar{K}_6)}$	Eq. (7–34)

*S'_e and S_{ut} in kpsi, d and d_e in inches.

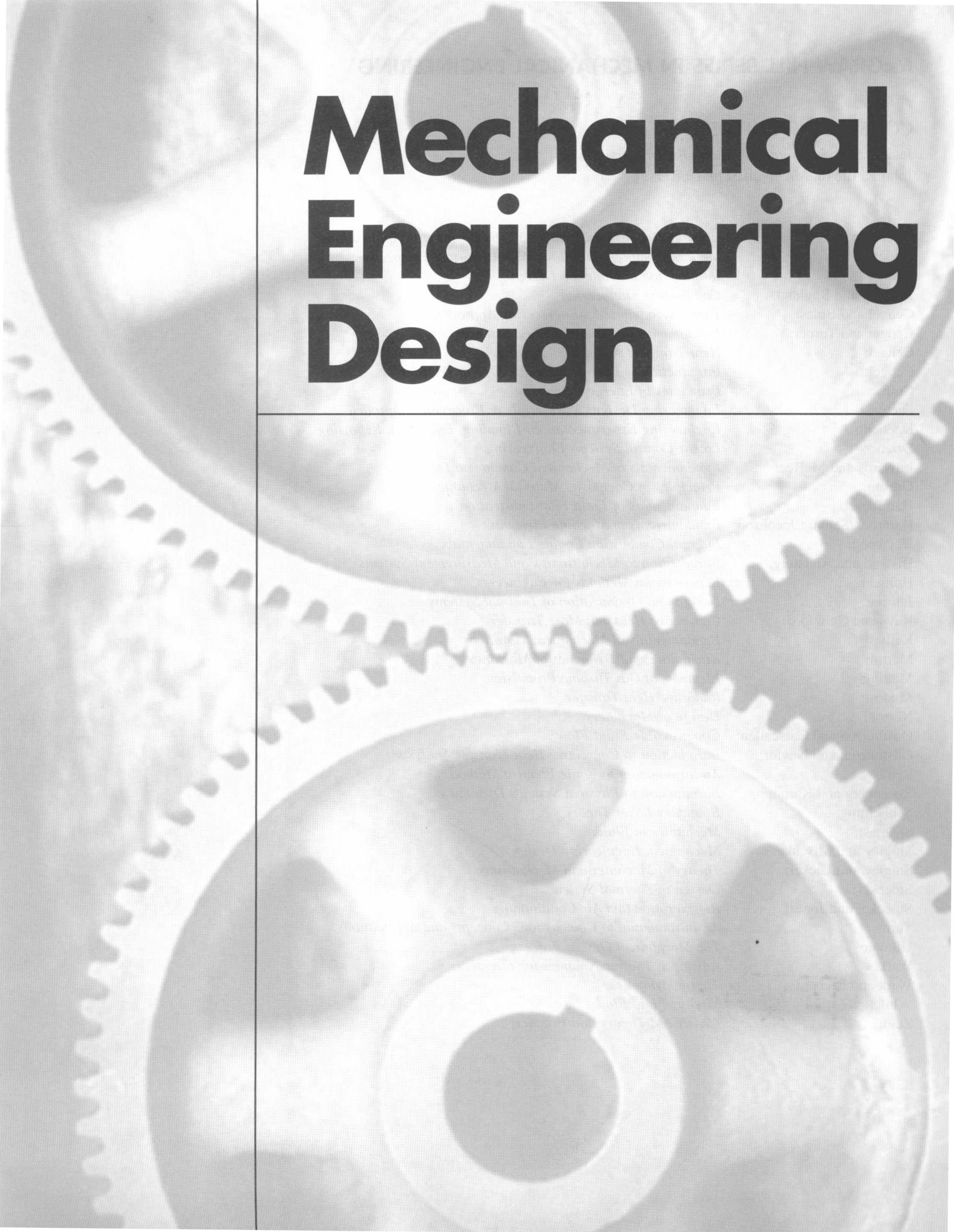
Table 7–14

Summary of Fatigue Equations $\mathbf{S}_e = \mathbf{k}_a k_b \mathbf{k}_c \mathbf{k}_d \mathbf{k}_e \boldsymbol{\phi}_{0.30} \bar{S}_{ut}$ in SI Units for Steels*

Quantity	Relation	Table or Equation
Ultimate strength	$\mathbf{S}_{ut} = 3.41(1, 0.041)\mathbf{H}_B$	Eq. (5–23)
Fatigue ratio	$\boldsymbol{\phi}_{0.30} = 0.506\mathbf{LN}(1, 0.138),\ \bar{S}_{ut} \le 1460$ MPa	
Endurance limit		
Bending	$\mathbf{S}'_e = \boldsymbol{\phi}_{0.30}\bar{S}_{ut} = 0.506\bar{S}_{ut}\mathbf{LN}(1, 0.138),\ \bar{S}_{ut} \le 1460$ MPa	
Axial	$(\mathbf{S}'_e)_{ax} = 0.724\bar{S}_{ut}^{-0.0778}\bar{S}_{ut}\mathbf{LN}(1, 0.264)$	Above Eq. (7–20)
Torsion	$\mathbf{S}'_{se} = 0.130\bar{S}_{ut}^{0.125}\bar{S}_{ut}\mathbf{LN}(1, 0.263)$	Above Eq. (7–20)
Surface factor		
Ground	$\mathbf{k}_a = 1.58\bar{S}_{ut}^{-0.086}\mathbf{LN}(1, 0.120)$	Table 7–5
Machined, CR	$\mathbf{k}_a = 4.45\bar{S}_{ut}^{-0.265}\mathbf{LN}(1, 0.058)$	Table 7–5
Hot-rolled	$\mathbf{k}_a = 58.1\bar{S}_{ut}^{-0.719}\mathbf{LN}(1, 0.110)$	Table 7–5
As-forged	$\mathbf{k}_a = 271\bar{S}_{ut}^{-0.995}\mathbf{LN}(1, 0.045)$	Table 7–5
Size	$k_b = (d_e/7.62)^{-0.107} = 1.24d_e^{-0.107}$	Eq. (7–10)
Loading factor		
Bending	$\mathbf{k}_c = \mathbf{LN}(1, 0)$	Eq. (7–20)
Axial	$\mathbf{k}_c = 1.43\bar{S}_{ut}^{-0.0778}\mathbf{LN}(1, 0.125)$	Eq. (7–21)
Torsion	$\mathbf{k}_c = 0.258\bar{S}_{ut}^{0.125}\mathbf{LN}(1, 0.125)$	Eq. (7–22)
Temperature factor	$\mathbf{k}_d$ (as applicable)	Eqs. (7–23), (7–24)
Miscellaneous factor	$\mathbf{k}_e$ (as applicable)	
Stress-concentration		
Infinite life	$\mathbf{K}_6 = (\mathbf{K}_f)_{10^6} = \dfrac{K_t\mathbf{LN}(1, C_{Kf})}{1 + \dfrac{2}{\sqrt{r}}\dfrac{K_t - 1}{K_t}\sqrt{a}}$	Table 7–12
Finite life	$\bar{K}_3 = (\bar{K}'_f)_{10^3} = 1 + \left[(\bar{K}_f)_{10^6} - 1\right]\left[-0.18 + 0.624(10^{-3})\bar{S}_{ut} - 0.948(10^{-7})\bar{S}_{ut}^2\right]$	Eq. (7–27)
	$\bar{K}_N = \dfrac{\bar{K}_3^2}{\bar{K}_6} N^{(-1/3)\log(\bar{K}_3/\bar{K}_6)}$	Eq. (7–34)

* S'_e and S_{ut} in MPa, d and d_e in mm.

Mechanical Engineering Design



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Dedication

To the over 3500 of my students who asked many good questions of me, learned to ask them of themselves, to answer them, and then went on to make their Alma Maters proud.

Charles R. Mischke

About the Authors

Charles R. Mischke has held positions on the faculty of the University of Kansas, was professor and chairman of mechanical engineering at Pratt Institute in New York, and professor of mechanical engineering at Iowa State University. He was named Alcoa Foundation Professor in 1974, received the Ralph R. Teeter Award of the Society of Automotive Engineers in 1977, received Iowa State's Outstanding Teaching Award in 1980, named Fellow of the American Society of Mechanical Engineers in 1986, received the Association of American Publishers Award in 1987, the American Society of Mechanical Engineers Machine Design Award in 1990, the Iowa Legislature Teaching Excellence Award in 1991, the Ralph Coats Roe Award of the American Society for Engineering Education in 1991, Life Fellow of A.S.M.E., 1993, and the Centennial Certificate of A.S.E.E. in 1993.

In addition to many research papers he authored *Elements of Mechanical Analysis*, 1963, *Introduction to Computer-Aided Design*, 1968, *Mathematical Modelbuilding*, 1980, eight Mechanical Designers Notebooks, 1990, coauthored *Mechanical Engineering Design*, 5th ed., 1989, and was Coeditor-in-Chief of the *Standard Handbook of Machine Design*, 1986, 1996.

He was awarded the BSME and MME degrees of Cornell University, and the Ph.D. of the University of Wisconsin. He is a licensed Professional Engineer in Iowa and Kansas. He is a member of the Iowa Railroad Historical Society, and a diesel locomotive engineer on the B&SV Railroad.

Joseph E. Shigley (deceased May 1994)
He was Professor Emeritus at the University of Michigan, Fellow in the American Society of Mechanical Engineers, received the Worcester Reed Warner medal in 1977, and their Machine Design Award in 1985. He was the author of eight books, including *Theory of Machines and Mechanisms* (with John J. Uicker, Jr.), and *Applied Mechanics of Materials*. He was Coeditor-in-Chief of the *Standard Handbook of Machine Design*. He began *Machine Design* as sole author in 1956, and it evolved into *Mechanical Engineering Design*, setting the model for such textbooks.

He was awarded the B.S.M.E. and B.S.E.E. degrees of Purdue University, and the M.S. of the University of Michigan.

Joseph Edward Shigley indeed made a difference.

Preface to the Student

Design is the essential task of engineering. Engineers who do not design, support the designer. Whether you design or not, you must understand it, and have knowledge of the designer's needs in order to effectively help. The course that uses this text will start you down this path.

Design is learned with and under a master designer. There are talents and bodies of knowledge that a designer needs.

- Knowledge, ability, talent to generate ideas, possibilities.
- Knowledge of how to evaluate ideas and sort wheat from chaff.
- Knowledge of the structure of design, and how to tailor the process to the task at hand.

These bodies of knowledge are largely independent of the necessary knowledge about how the universe behaves. Design can be learned, and it is the role of this course to begin the process. Industrial experience and your mentors will continue the process.

In this book you will stand on a large amount of prerequisite information. We will bring it together as it applies to machinery, extend it further, and add to your knowledge about the universe. This is essential business to be sure, but it does not address the design process. As we move along in the first two parts of the book, some design ideas will be folded in. Just because they are initially in the minority doesn't mean they are unimportant. Then, as we begin Part 3, we can do "little designs" as we learn about individual machine elements. As we go further we can and will do more.

If you, your instructor, and the authors all do our parts, you will be largely unaware of the folding together of knowledge of the universe and knowledge about design. It's akin to the background music in a dramatic movie. If it is well done, the response to the question, "How did you like the music?", can be another query, "What music?"

Of course, machinery design is not an emotional, but an intellectual experience, and you must stay attentive. You will find it very interesting.

Charles R. Mischke
Ames, Iowa

Preface to the Sixth Edition

Course and Prerequisites

This book has been written for engineering students who are beginning a course of study in mechanical engineering design. Such students will have acquired a set of engineering tools consisting, essentially, of mathematics, computer languages, and the ability to use the English language to express themselves in the spoken and written forms. Mechanical design involves a great deal of geometry, too; therefore, another useful tool is the ability to sketch and draw the various configurations that arise. Students will also have studied physics and a number of basic engineering sciences, including engineering mechanics, mechanics of materials, materials science, manufacturing as well as heat, mass, and momentum transport. These, tools and sciences, constitute the foundation for the practice of engineering, and so, at this stage of undergraduate education, it is appropriate to introduce some professional aspects of engineering. These professional studies should integrate and use the tools and sciences to the accomplishment of an engineering objective. The pressures upon the undergraduate curricula today require that we do this in the most efficient manner. Most engineering educators are agreed that mechanical design integrates and uses a greater number of the tools and disciplines than any other professional study. Mechanical design is also the very core of other professional and design types of studies in mechanical engineering. Thus studies in mechanical design seem to be the most effective method of starting the student in the practice of mechanical engineering.

One of the reasons for preparing a new edition now is the recent emphasis on the creative aspect of design. In the early 1950s a committee on evaluation of engineering education of the American Society for Engineering Education stated:

> "Training for the creative and practical phases of economic design, involving analysis, synthesis, development, and engineering research, is the most distinctive feature of professional engineering education."

> "The technical goal of engineering education is preparation for performance of the functions of analysis and design, or of the functions of construction, production, or operation with full knowledge of analysis and design of the structure, machine or process involved."

Though these goals were stated nearly 50 years ago, they are valid today. Ways must be found to involve the engineering student in genuine design experiences.

Approach

The approach of this book is to suggest and present short design problems or situations to illustrate the decision-making process without demanding an inordinate amount of the student's precious time. Good short design projects are certainly needed in the professional design studies. These are most effective when they are created from the instructor's own professional background and presented with enthusiasm and thoroughness which this background allows. With such an approach new and updated projects can always be devised to meet current needs and ideas.

Additional major reasons for publishing this new edition include

- Addressing uncertainty with more quantitative assurance.
- Reliability goals need to be met.
- Methodology now exists for the estimate of the chance of failure.
- Design and analysis methodologies need to be intertwined.
- There is a need for an increased number of examples, and many new problems.
- The fading of mainframe computers, and the increasing use of personal computers, networked, makes an impact on engineering use.

Uncertainty in Engineering Design

Uncertainty plagues the designer. He or she needs the ability to express it quantitatively, so that decisions can be sound. The traditional deterministic approach to design simply cannot cope with the problem of uncertainty. It is not that one must learn an entirely new way of approaching problems. The deterministic approach is not to be lost. The traditional methodology simply propagates the mean values through the problem. One has to learn how to propagate the variability through the problem. The Accrediting Board for Engineering and Technology is requiring student ability to apply statistics to engineering problems. The basic statistical knowledge is either scattered among several engineering courses, or concentrated in a formal statistics course. Fortunately we often only have to organize a little statistics in order to find the mean design factor which will permit the attainment of the reliability goal. After that, the problem can be treated deterministically. We also learn how poorly we know some basic information, and we have to accommodate to that vagueness. Product liability and quality control concerns can be addressed as needed.

If one addresses uncertainty quantitatively, then in and among that information are the tools for expressing reliability. The methodology now exists for quantitative estimation of the chance of failure. There are data to allow this in steels. Since reliability is one minus the probability of failure, we can quantitatively estimate the chance of survival. This opens the door to designing to a reliability specification.

Design Content

DESIGN

Some engineers look forward to receiving a design task, and the blank pieces of paper that go with it. Other engineers do not look forward to either. Part of the dichotomy during the educational process is attributable to design and analysis being separated. Design content at the end of a course gets less attention. To ensure that both design and analysis get consideration, they are blended in this edition. As a guide to both student and instructor, end-of-chapter problems are identified as to kind. There are 775 problems, half of which are new.

Examples

A noticeable change is an increase in the number of examples; first for the improvement of clarity, second, to allow illustration of new material, and third, to address the subtleness of the additional design content. The increased emphasis on design requires development of a designer's viewpoint early in the book, and many threads have to be carried throughout all the chapters. There are many more examples, which are revisited in later examples, and in end-of-chapter problems. Examples in earlier chapter are revisited.

Curriculum time allotments require that this be done without increasing the course time. Many ideas and experiences have to be interwoven with the subject-matter to allow sufficient repetition for learning and retention. A viewpoint develops, which increases confidence and reduces apprehension in the face of the unknown.

Computer Use

Access to mainframe computers continues, but, increasingly, personal computers are available to students, and many handheld calculators are miniature computers that go everywhere with the student. All this makes computing a powerful tool to be reached for when needed. Programming is no longer a "big deal." Today's student can do the same in less time, or more in the same time. Simulations can be conducted and parametric studies allow broader and more global views than heretofore. A book such as this doesn't have to provide programs for everything, although there are a few. Just listing algebraic and logical steps in algorithmic form is enough to get the student "off and running." The book takes advantage of this for the learning process. Computer-oriented problems are marked with an icon.

One of the roles of a book such as this is to do the necessary chores for the student and the instructor in a methodical and sequenced way, freeing the instructor to be more of a coach, and enabling the instructor to specifically accomplish syllabus objectives. The book reduces the instructor's need to "cover" material. The instructor is freer to mold and build a framework for knowledge and approach, and to answer the many questions that arise as students feel their way. There are highlighted Case Studies in chapters for which newly-acquired background makes the student receptive, and provides an opportunity for the instructor to make coaching points while asking pointed questions. Adequacy assessment is the designer's primal skill. Problems involving this skill are marked with an analysis icon, and the words adequacy assessment are added in the margin, or in the problem statement.

Organization and Content

The book is still in three parts. Part 1 is basic and includes a more comprehensive introduction, definitions, statistical considerations, stress analysis, deflection, and stiffness estimation. The student will be prepared on most of these topics, but not always. The basic material may need some presentation, if only to serve as a review of basic reference material, always in the hands of the student, and presented in the symbolism and terminology of the subsequent parts of the book. Readers will notice a little history has been added. Some material useful in mentoring has been added for both the student and the instructor to "mull over."

Part 2 addresses failure prevention. It makes use of and integrates the fundamentals of Part 1 toward the goal of analyzing and designing mechanical elements to achieve satisfactory levels of preserving function, safety, reliability, competitiveness, usability, manufacturability, and marketability.

Part 3 examines specific mechanical elements such as fasteners, weldments, adhesives, springs, bearings, gears, clutches, brakes, shafts, belts, chains, and so on, and specifically addresses analysis, selection, and design. The new material in Parts 1 and 2 has greatly enhanced the development and presentations in Part 3. It gives the instructor wider opportunities to augment, enrich, and pursue goals outside the scope of the book.

Chapter 1, *Introduction,* contains a fuller treatment of design ideas (and history) and raises some important considerations early. The task of assuring that a product is functional, safe, reliable, competitive, usable, manufacturable, and marketable is presented immediately, along with the design imperative. The subsequent engineering tasks are presented. The different goals of science (to explain what is, and why) and engineering (to create what never was) and the differing skills are noted. The necessary talent in both cases is identified. Suitability, feasibility, and acceptability tests are presented. Specification sets, decision sets, adequacy assessments, and Skill 1 are initially defined. Figures of merit, optimization, synthesis, and Skill 2 are also discussed. Since the reader has embarked on a path to competence, mileposts (kilometer sticks?) are cited along with the changing *modi operandi,* so that the student is aware of the nature of the game being played at the outset. The fragility of technology is noted, the importance of the designer's notebook is mentioned, and the role of the computer is identified.

Uncertainty is ubiquitous, and continually plagues the designer, and its historical treatment is traced. Insightful contributions to bending are noted, and the engineer's debt to Professor Irving P. Church of Cornell University is acknowledged. Factor of safety ideas are identified with more precision than is the usual case. Useful distinctions among the seven kinds of numbers engineers use are made. The adequacy assessment is introduced in broad description for its continual expansion and development throughout the book.

Chapter 2, *Addressing Uncertainty,* has been completely rewritten to support ABET's increased emphasis on statistical applications in design, and to demonstrate the rational treatment of uncertainty. Additional information has been included in Appendices A, B, C, and D.

Chapter 3, *Stress,* has had material added on open and closed thin-walled sections, the Smith–Liu equations for contact stresses in the presence of surface shearing traction, as well as propagation of error.

Chapter 4, *Deflection and Stiffness,* now includes snubbers, round-bar clamps, and concludes with propagation of error examples illustrating the four cases of Chapter 3 applied to relations between load and distortion.

Chapter 5, *Materials,* has had information added which shows the limitation of single-number tables of material properties. There is additional text on plastic deformation, quantitative estimation of properties of cold-worked metals (method of Datsko), and some direction on where to find quantitative treatments of properties of heat-treated steels.

Chapter 6, *Failures Resulting from Static Loading,* addresses assessment of static strength, distinguishes between hypotheses of failure and theories of failure, and addresses criticism of hypotheses in ductile and brittle materials, then considers what our theories of failure tell us, with a number of examples. Static and quasi-static shaft stress analysis concludes the chapter.

Chapter 7, *Failures Resulting from Variable Loading,* addresses fatigue. New information is presented about the tensile strength correlation method, and what it has to say about fatigue ratio and its variability. Included are improved estimations of a and b of $S_f = aN^b$ when the true stress at fracture σ'_f (available from the static tensile test) is known, or can be well-estimated from $\overline{S}_{ut}$. Marin endurance limit modification factors are presented for both stochastic and deterministic approaches. More information is given on relating fatigue stress-concentration factor $\mathbf{K}_f$ to notch-sensitivity factor $\mathbf{q}$. The modified Neuber equation for stress concentration factor $\mathbf{K}_f$ (after Heywood) is given and used because its statistical basis is more extensive than the notch-sensitivity q (after Peterson). A section replete with examples is presented applying what was learned about endurance limit and endurance strength. After characterization of fluctuating stresses, fatigue failure loci are identified. Those cannot be rejected statistically

(Gerber-parabolic and ASME-elliptic) are used principally. Those that can be rejected (Goodman and Soderberg) are included briefly for completeness, so that we can follow the work of others, if necessary. Cumulative fatigue damage includes a modified rain-flow technique. Surface fatigue information has been augmented. The designer's fatigue diagram is presented, and a shaft analysis for fatigue completes the chapter.

Chapter 8, *Screw Fasteners and the Design of Nonpermanent Joints,* addresses threaded fasteners principally, with some attention to pins and miscellany. Addition material is presented on identifying threaded and unthreaded length within a joint fastener in order to improve the bolt stiffness estimate. Because of the reader's improved stochastic understanding, initial tightening can be treated statistically, and preload given a more complete treatment because of the insights available. More material on gaskets is presented. Specification set and decision set ideas are further developed. An example of a pin failure is included.

Chapter 9, *Welding, Brazing, Bonding, and the Design of Permanent Joints,* treats weldments principally, with more material relating to the difference between an analytical, and a throat-stress approach to sizing of welds. More weld-fatigue information is included. Adhesive bonding presentation has been expanded.

Chapter 10, *Mechanical Springs,* has been revised to take advantage of what the topic can teach, and the student can learn, about design. Care has been taken to distinguish between stress-concentration factors and stress-augmentation factors. Additional material on moduli of elasticity has been incorporated. Fundamental zero-max test information is the starting point for a fatigue failure locus on the designer's fatigue diagram. Such a test is carried out on actual springs, and so includes surface, size, and loading effects. However the test cannot be run to zero stress, so it is run from a low stress to a maximum. Just the act of reducing the data to a zero-max basis requires adopting a failure locus type (Goodman, Wahl, Sines, Gerber or ASME-elliptic). Published data rarely identifies the hypothesis, and a fundamental point is in doubt. Differing zero-max properties for the same material from different investigators underscore the problem.

The chapter presents analyses, adequacy assessments, specification sets and decision sets, and gives examples for helical-coil compression springs, helical-coil extensions springs, and helical-coil torsion springs.

Chapter 11, *Rolling Contact Bearings,* recognizes that L_{10} ratings, which are the basis for many manufacturer's catalogs, are too low for machinery use. Consequently, the load-life-reliability tradeoff relations of rolling-contact bearings are a central focus. Distinctions are drawn between stepwise-constant and continuously varying loads, and the methodology for treating them is included. Variable loading on rolling-contact bearings is addressed in such a way that the Miner rule drops out of a linear-damage hypothesis. The section on selection of tapered-roller bearings has been expanded. The question of misalignment is included.

Chapter 12, *Lubrication and Journal Bearings,* begins with Petroff's equation, an early quantitative model of a journal bearing. From this model the Sommerfeld number was (inappropriately) defined. Since that definition persists, the nature of the deviation is shown. The introduction to hydrodynamic theory of the previous edition is presented. In design considerations Trumpler's criteria for journal bearings is presented and used. Raimondi and Boyd charts are combined with Trumpler's criteria. Bearing temperature rise is given more attention than previously, and more examples are provided. Adequacy assessments and decision sets are explored.

The above approach is applied to pressure-fed bearings as well. With these fundamentals in mind, the problem of journal and bushing tolerance is discussed. The result of this is the realization that all journal-and-bushing assemblies are different bearings with different properties. The design-window viewpoint recognizes this.

Boundary lubrication and wear are examined in more detail than in the previous edition. Design procedures are presented, with example.

Chapter 13, *Gearing—General,* is an introduction to four of the principal types of gearing. Interference in spur and helical gearsets is treated more quantitatively than before. Forces and moments are the primary emphasis. Additional attention is given to tooth-count and mechanical efficiency. A planetary gear train is examined to identify the appropriate Sommerfeld numbers.

Chapter 14, *Spur and Helical Gears,* has been modified to reflect the current ANSI/AGMA standards, including velocity factor K_V which is now the reciprocal of K_V heretofore. Surface durability, bending fatigue and factors of safety are explored. Analysis "maps" are provided as well as adequacy assessments of gear meshes. The design of spur and helical gear meshes is laid out in detail, with examples.

Chapter 15, *Bevel and Worm Gears,* begins with ANSI/AGMA standards, and provides analysis "maps" for bending and pitting resistance of straight-bevel gears. Worm gearing begins with an ANSI/AGMA standard for cylindrical worms. An example of a worm-gear mesh is provided. The design of a worm-gear mesh, beginning with a decision set is included. The Buckingham wear-load equation is presented, which allows for analysis and design of cylindrical-worm gearing with other than the hard steel worm and the bronze wheel material combinations.

Chapter 16, *Clutches, Brakes, Couplings, and Flywheels,* has additional material. Brakes are introduced with the relationships surrounding a door stop to identify the essential ideas. The internal brake shoe pressure distribution is derived from fundamentals, and applied. External brake shoes follow. Band-type clutches and brakes are explored. Clutch and brake relationships are summarized dimensionlessly, and there are valuable things to be learned from doing this. Frictional-contact axial clutches are included. Caliper brakes are examined quantitatively. Cone clutches and brakes are closely related to axial clutches and brakes.

Self-locking tapers are examined and their relationship to clutches and brakes explored. Temperature-rise in clutches and brakes is treated quantitatively.

Chapter 17, *Flexible Mechanical Elements,* now provides more insight into flat belt theory, and examines the impcrtance of initial tension. Attention is given to ways to achieve initial tension and to sustain it. The decision set for specifying a flexible flat belt is identified. Metal flat belts are introduced, with example, and durability is examined. V belts are presented along with the importance of initial tension. Attention is given to life expectancy. Adequacy assessments, specification set and decision sets are identified, and the similarity to flat belts noted. Roller-chain rating basis is presented in more detail. Design life other than 15 000 h is quantitatively studied. The presentation of wire rope includes adequacy assessment, specification set and decision set, and an example of a minehoist is provided to show the relationship between nominal wire rope diameter, number of supporting ropes and fatigue factor of safety.

Chapter 18, *Shafts and Axles,* begins with a plan for addressing the task of shaft design, sufficing static and fatigue constraints, sufficing geometric constraints, with examples. In the process distortion-energy—Gerber and distortion-energy—elliptic equations are emphasized. The adequacy assessment for strength for both stochastic and deterministic approaches is illustrated by example. The preparation of the student to compare and contrast the methods, and, what they can and cannot accomplish is at hand. This is addressed. Shaft material and hollow shafts have brief presentations. Critical speeds have now been added. With the foregoing background an approach to shaft design is described. Computer considerations are identified. Programming Task No. 3 that completes the chapter is an important opportunity for a student to develop an insight.

The Appendix has had some additions. Three of the charts for geometric stress-concentration factors K_t and K_{ts} have been replaced by the results of finite element studies. Two additional tables giving stochastic parameters of strength distribution are included, along with two tables of dimensions of American Standard Plain Washers, the gamma function, the correlation coefficient *r*, the *t*-statistic, and several helical spring specification forms.

Supplements

This edition is supported by a number of supplements, made available to adopters through the publisher.

Solutions Manual—an instructor's manual which contains solutions to most end-of-chapter nondesign problems.

PowerPoint® Slides—approximately 200 slides of important figures and tables from the text are provided in PowerPoint format for use in lectures. These files are available on the book website.

Website—a website for the book has been established at www.mhhe.com/engcs/mech/shigley. This site contains information about the text, text updates and errata, PowerPoint slides, and the password-protected solutions manual.

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